Jet Studies at Belle II: Measuring the Dijet Transverse Momentum Decorrelation

Simon Schneider
simon.schneider@duke.edu
Belle II Summer Workshop at ISU
2022-08-05

Research supported by the U.S. DEPARTMENT OF ENERGY | Office of Science

Duke UNIVERSITY

Our work within Belle II

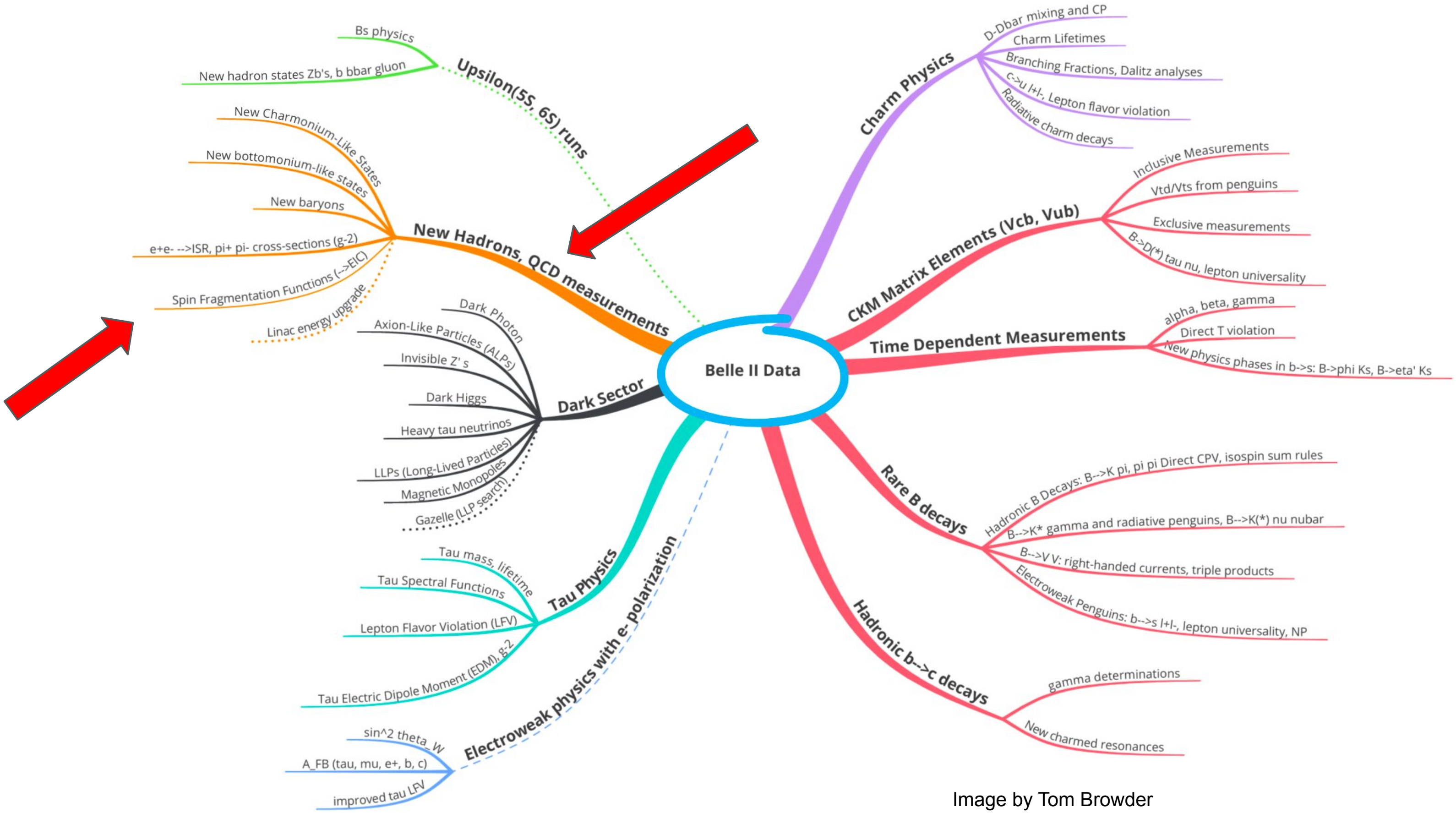


Image by Tom Browder

How to work with Jets

How to find jets: Anti-k_t algorithm for e^+e^-

1. For each pair of "particles" *i* and *j*, find the k_t distance

$$d_{ij} = \min\left(E_i^{-2}, E_j^{-2}\right)\frac{(1-\cos\theta_{ij})}{(1-\cos R)}$$

2. For each "particle" *i*, find the beam distance

$$d_{iB} = E_i^{-2}$$

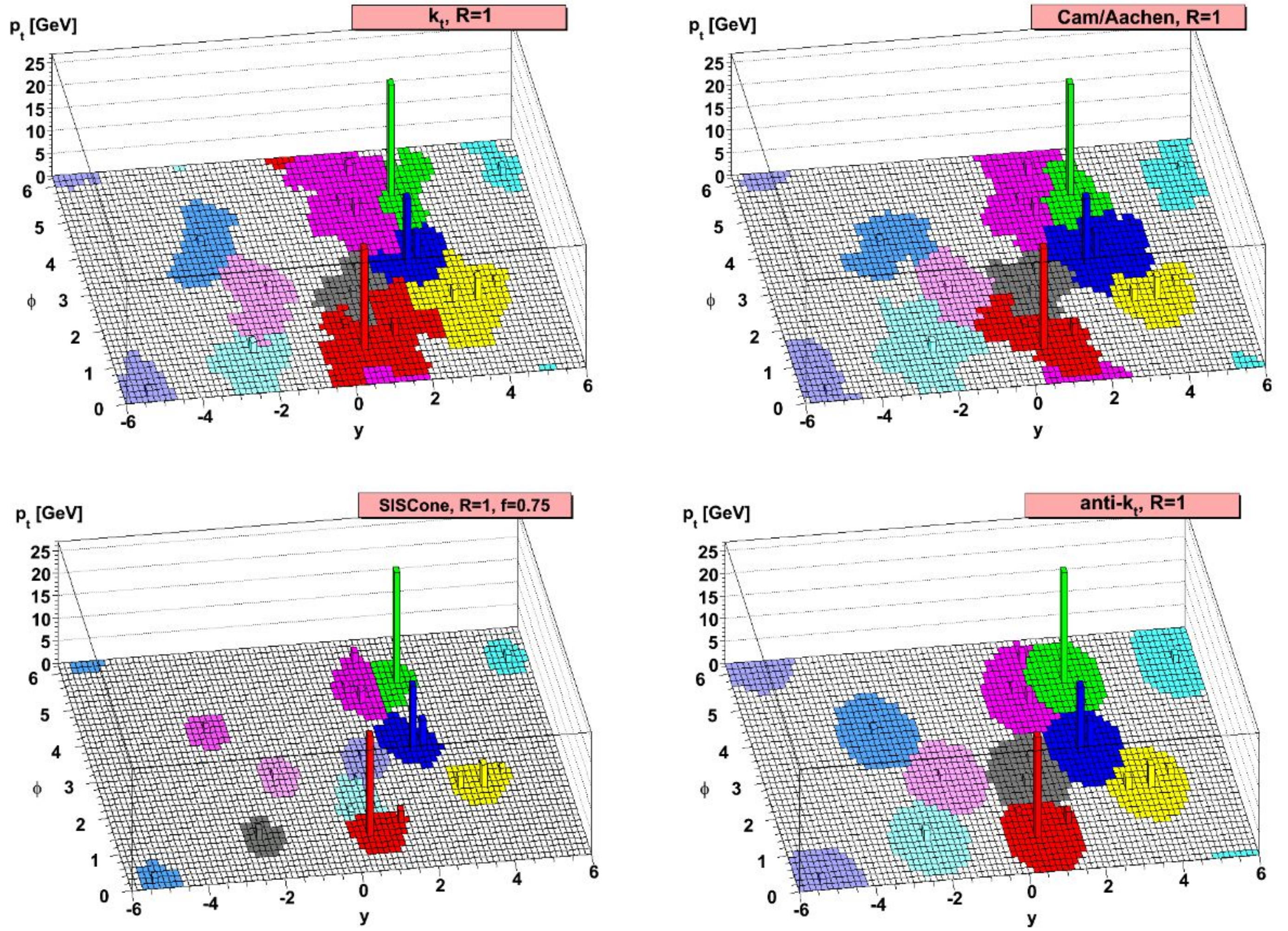
3. Find minimum of all d_{ij} and d_{iB} in the event
   If d_{ij} is smallest, then merge "particles" *i* and *j*
   If $d_{iB} < d_{ij}\ \forall j$, then call the "particle" *i* a jet and remove from list

4. Repeat until no "particles" are left

R: jet radius, a parameter of the algorithm

E: energy of the "particle"

θ: angle between "particles"



source: https://iopscience.iop.org/article/10.1088/1126-6708/2008/04/063/meta

Different recombination schemes

- Standard jet axis (SJA) recombination simply sums 4-vectors
- Winner takes all (WTA) scheme replaces two particles with massless particle moving in direction of more energetic particle, with new energy being the sum of both particles
  - Momentum of completed jet is parallel to momentum of most energetic constituent

$$\text{SJA}: \quad E_{(12)} = E_1 + E_2, \quad \vec{p}_{(12)} = \vec{p}_1 + \vec{p}_2\,,$$

$$\text{WTA}: \quad E_{(12)} = E_1 + E_2, \quad \vec{p}_{(12)} = E_{(12)}\left[\frac{\vec{p}_1}{|\vec{p}_1|}\theta(E_1 - E_2) + \frac{\vec{p}_2}{|\vec{p}_2|}\theta(E_2 - E_1)\right]$$

Here, θ is the Heaviside step function

Jets: Software

There is a convenient software package for both pp and e^+e^- experiments:

FastJet (http://fastjet.fr/)

"A software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation."

Even more convenient: FastJet has been included in the basf2 externals v01-10-00 and newer

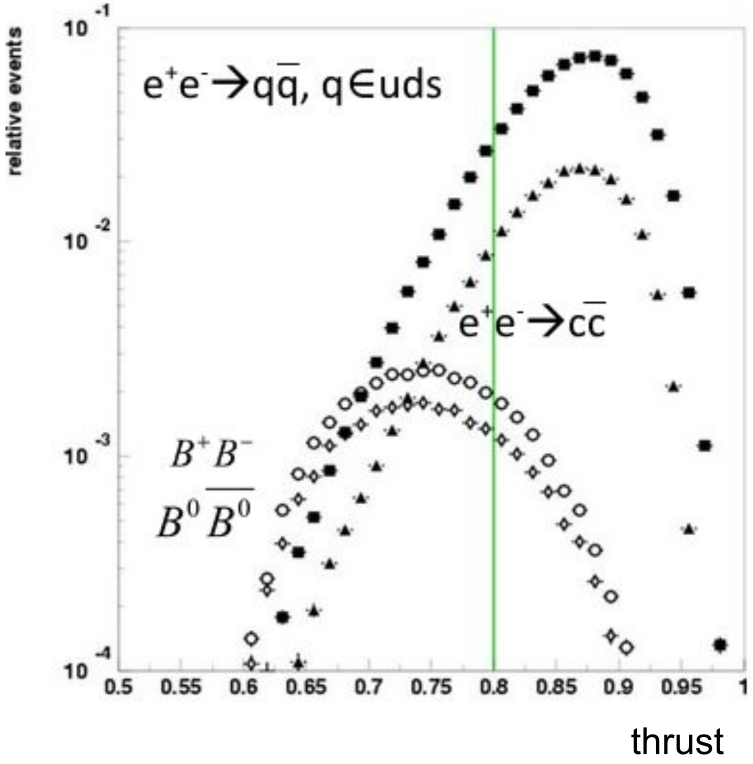
-> The software tools necessary to start jet studies at Belle II are in place!

(Let us know if you need help setting up FastJet for a basf2 analysis)

How to use a B-factory for jet physics

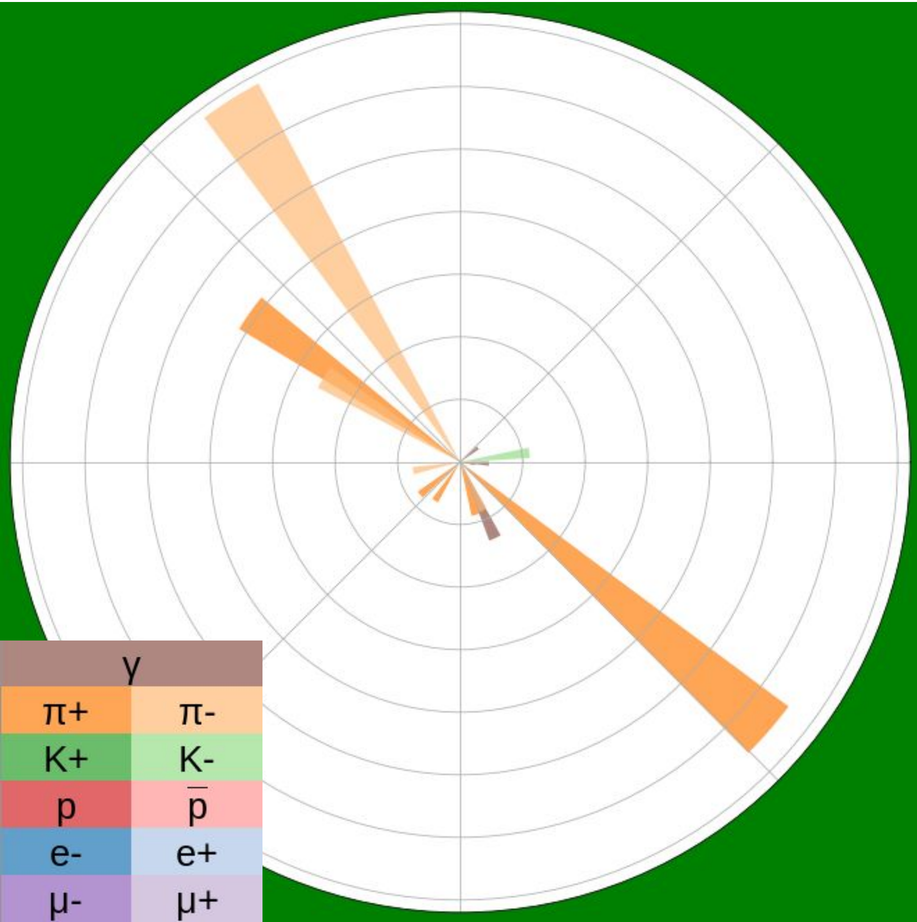
- Shapes of different event types are key
- Since they are produced at Y(4S), the $B\bar{B}$ events are very spherical
- Meanwhile $q\bar{q}$ events tend to form high-thrust dijet events
- Cuts on thrust or dijet energy provide clean $q\bar{q}$ dijet event sample

$$Thrust : T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

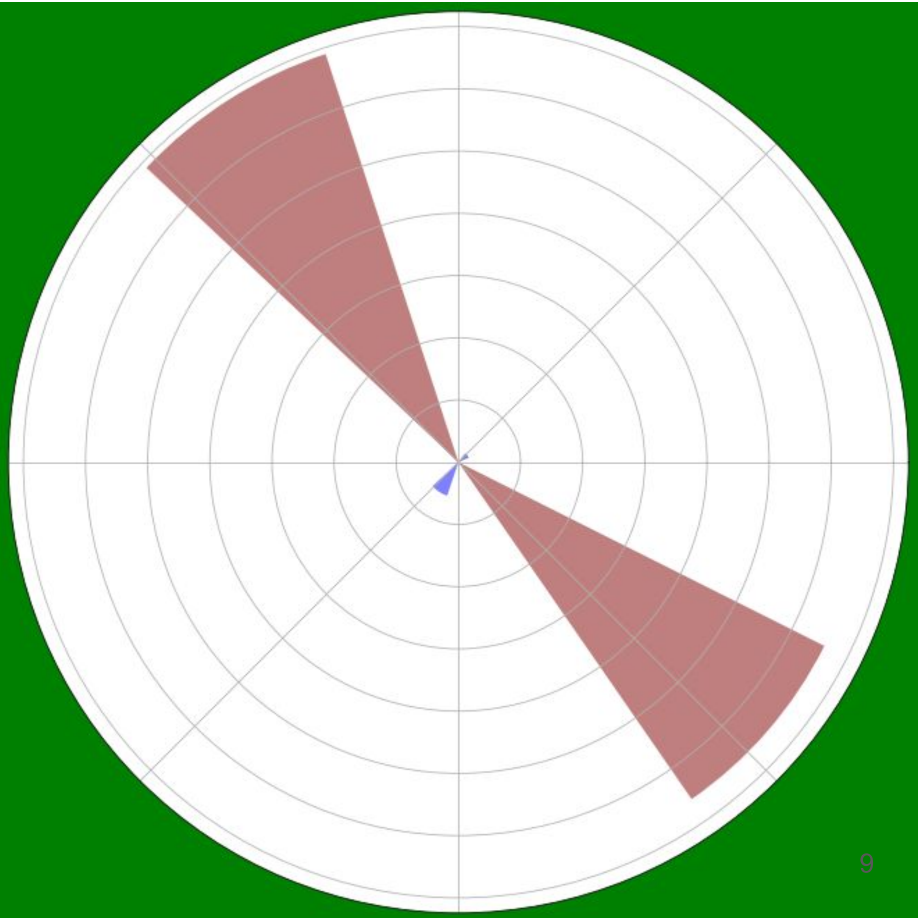


Dijet-like event

Particles

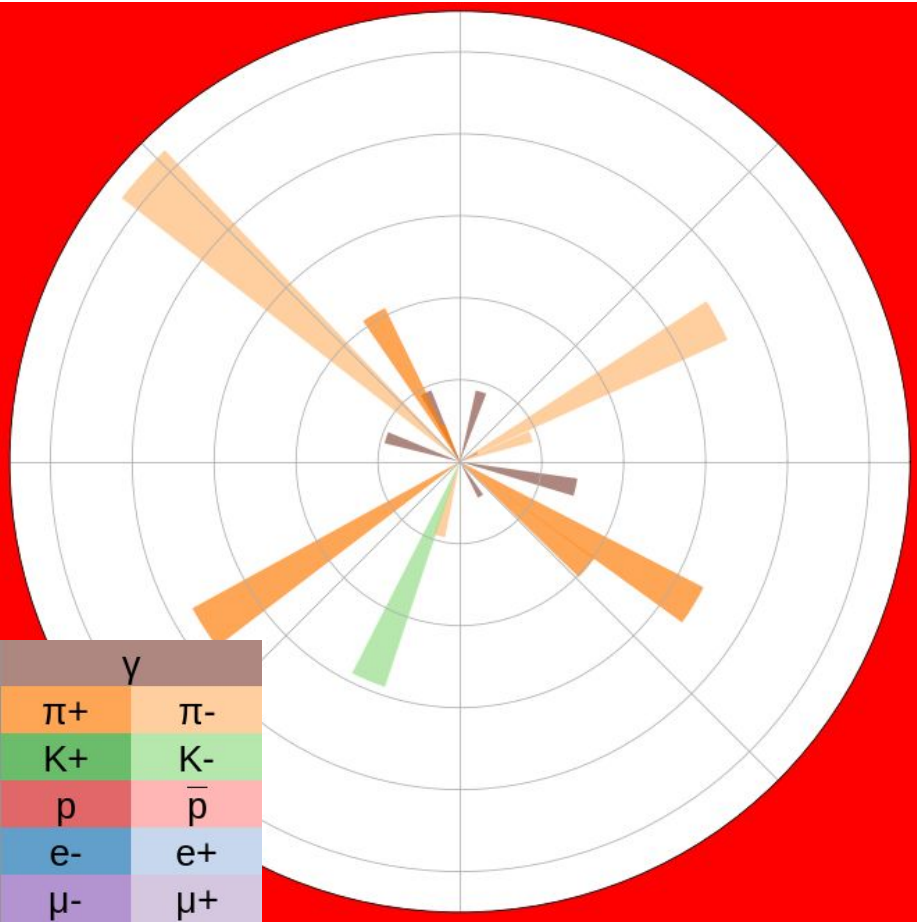


Jets

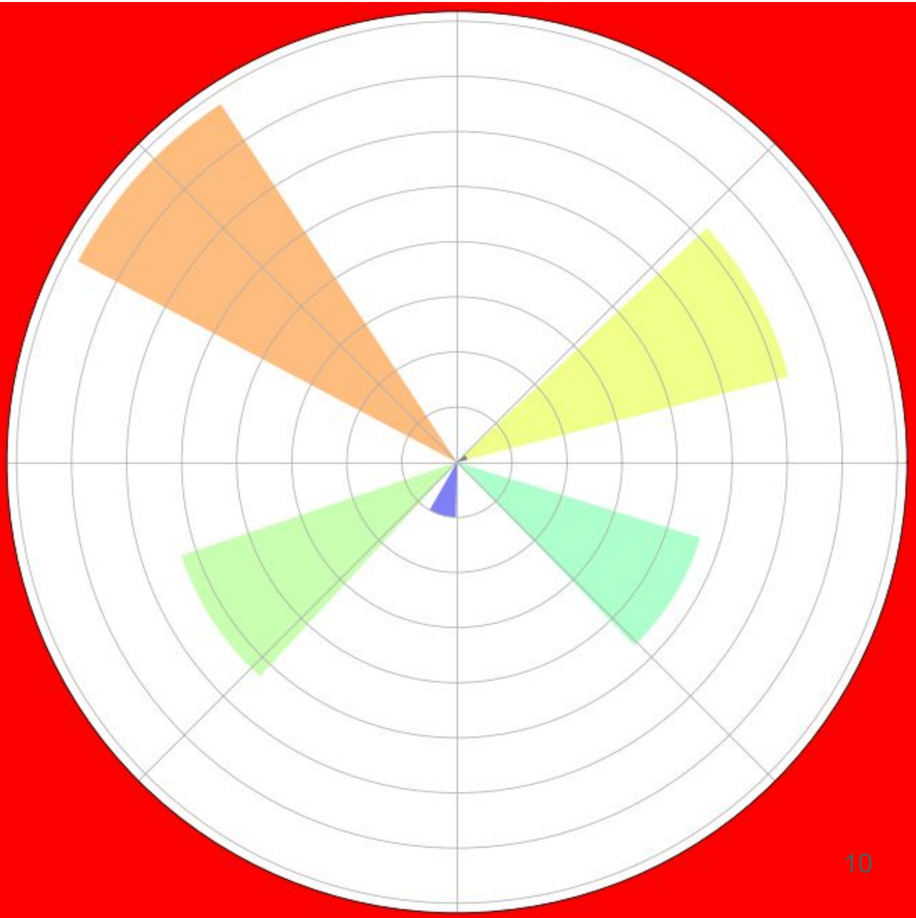


Spherical-like event

Particles



Jets



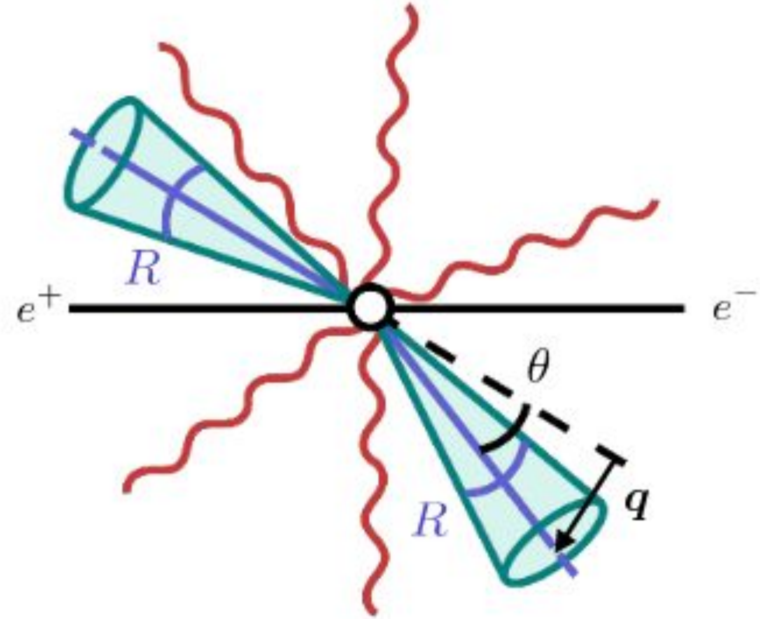
Measuring jet q_T spectrum at BELLE II: Definitions

Transverse momentum decorrelation ***q***:

$$\boldsymbol{q} = \frac{\boldsymbol{p}_1}{z_1} + \frac{\boldsymbol{p}_2}{z_2}\,, \qquad (e^+e^- \to \text{dijet})$$

$$q_T \equiv |\boldsymbol{q}| \ll \frac{\sqrt{s}}{2}$$

$$\theta = \arctan\left(\frac{2q_T}{\sqrt{s}}\right) \approx \frac{2q_T}{\sqrt{s}}$$



source: Gutierrez-Reyes, D., Scimemi, I., Waalewijn, W.J. *et al.* Transverse momentum dependent distributions in e^+e^- and semi-inclusive deep-inelastic scattering using jets. *J. High Energ. Phys.* **2019,** 31 (2019). https://doi.org/10.1007/JHEP10(2019)031

Motivation

- Why we care
  - Majority of jet physics results are from high energy hadron collisions
  - Need to test existing jet calculations across a wide energy range

- Why we do jet physics at Belle II
  - Large Belle II dataset in clean environment with good PID will allow precision and correlation studies and hadronization/QCD
  - Lower energies enhance access to transverse momentum dependent and non-perturbative effects
  - Possibility to test additional observables and effects not previously accessible in e^+e^-

- Relevance to the field
  - Measurement of the q_T spectrum serves as test of this extension to lower energies
  - Relevance for EIC and understanding hadronization

Measuring jet q_T spectrum at BELLE II

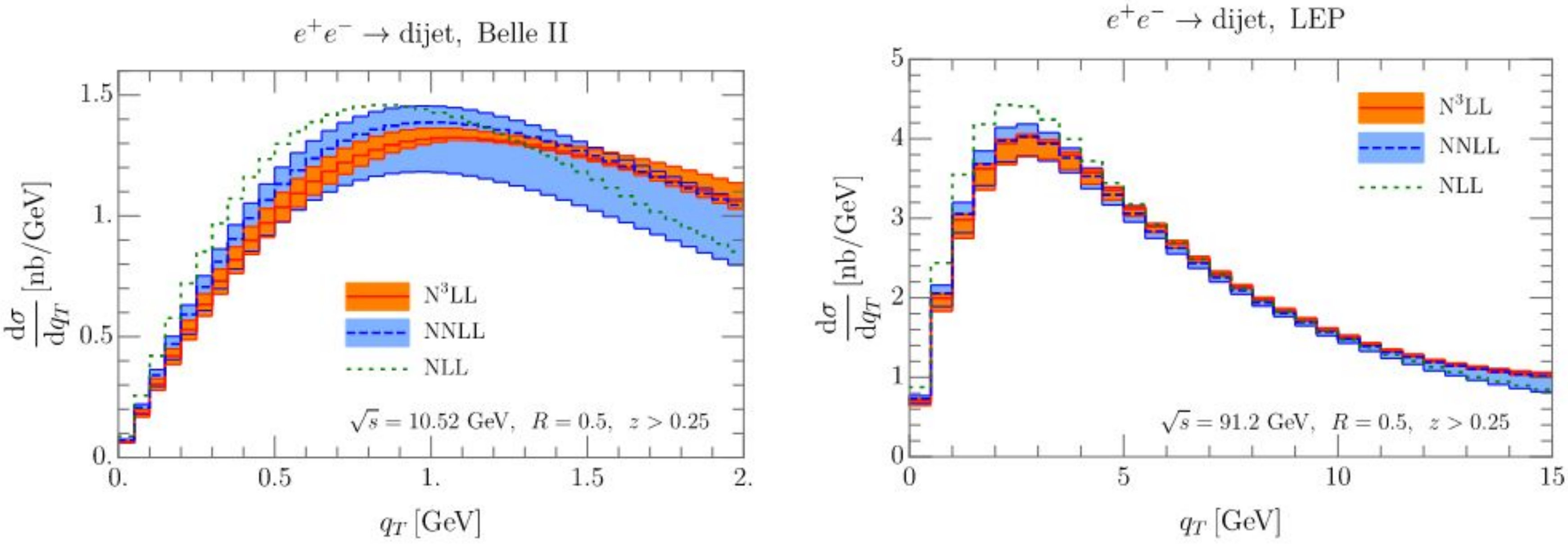
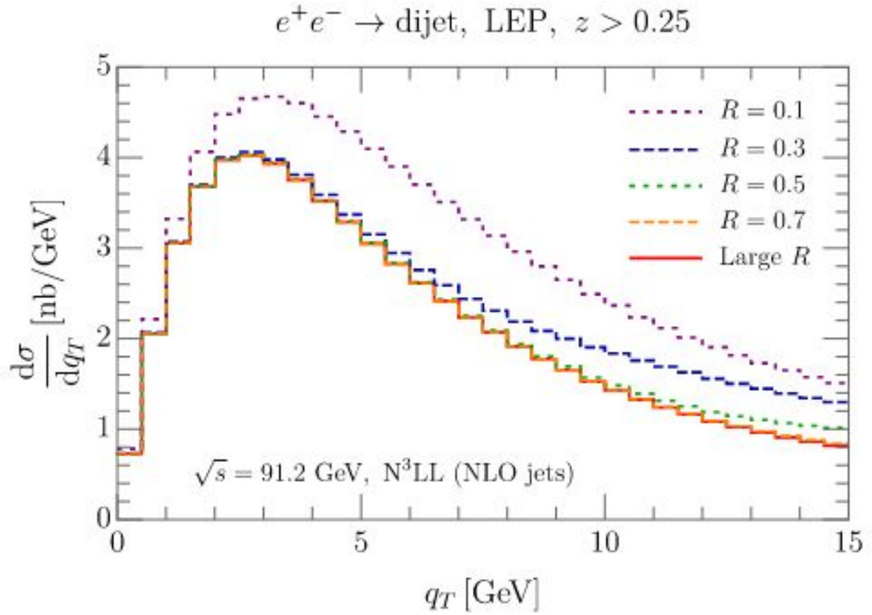
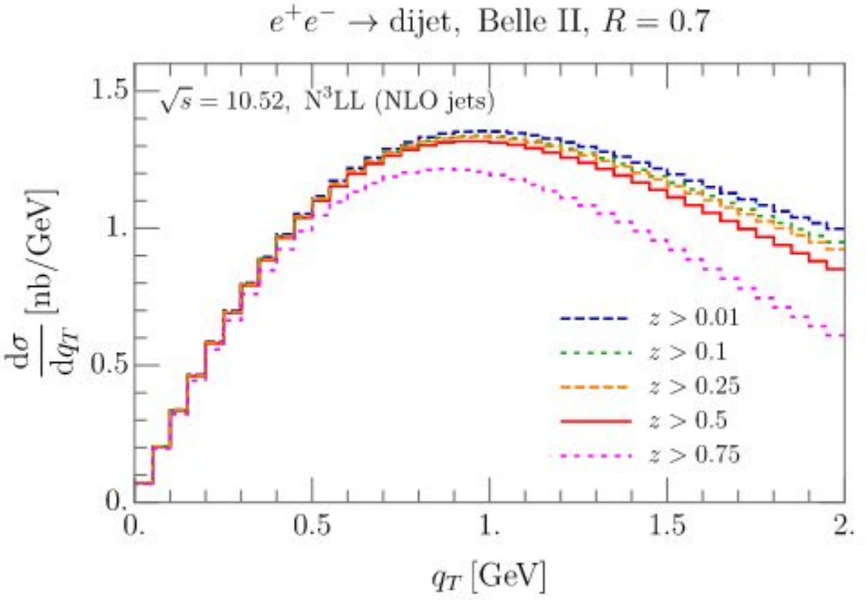


Figure 5. Perturbative convergence of the cross section differential in transverse momentum decorrelation, for Belle II (left) and LEP (right), for jet radius $R = 0.5$ and jet energy fraction $z > 0.25$. The N^{3}LL result is obtained with the prescription in eq. (6.1). The bands encode the perturbative uncertainty, as described in the text.

source: Gutierrez-Reyes, D., Scimemi, I., Waalewijn, W.J. *et al.* Transverse momentum dependent distributions in e^+e^- and semi-inclusive deep-inelastic scattering using jets. *J. High Energ. Phys.* **2019,** 31 (2019). https://doi.org/10.1007/JHEP10(2019)031

Can also check dependence on jet radius R and jet z cut





Calculations enabled by replacing regular fragmentation functions with jet functions
-> We can use Belle II to constrain non-perturbative corrections to jet functions

source: Gutierrez-Reyes, D., Scimemi, I., Waalewijn, W.J. *et al.* Transverse momentum dependent distributions in e^+e^- and semi-inclusive deep-inelastic scattering using jets. *J. High Energ. Phys.* **2019,** 31 (2019). https://doi.org/10.1007/JHEP10(2019)031

The q_T measurement in practice

- Event cuts: Selection of e^+-$e^-\rightarrow$dijet events
  - Require two highest energy jets to have E > 3.75 (z > 0.71)
- Finding appropriate track cuts / particle selection
  - Photon energy cuts (> 0.1 GeV)
- Choice of jet definition and recombination scheme
  - e^+-e^- anti k_t algorithm, WTA
- Determining detector effects
  - Find response matrix with MC study and unfolding
- Study R and z-cut dependence of q_T spectrum
- We expect systematic effects from:
  - Imperfect detector response
  - Non $q\bar{q}$ contributions to dijet-sample (e.g.tau pairs)
  - Initial state radiation (ISR) makes effective CMS energy uncertain

More possible measurements

- Many other jet-related observables can constrain QCD dynamics
  - Help understand limits of perturbative QCD
  - Constrain non-perturbative quantities
- Some examples:
  - Hadron-in-jet fragmentation
  - Energy-energy correlators
  - Momentum sharing fraction z_g
  - Jet charge
  - Flavor correlations
  - Jet pull
  - Jet angularities
  - T-odd effects
- See also:
  - "Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper" e-Print: 2204.02280 [hep-ex]

Backup slides and notes

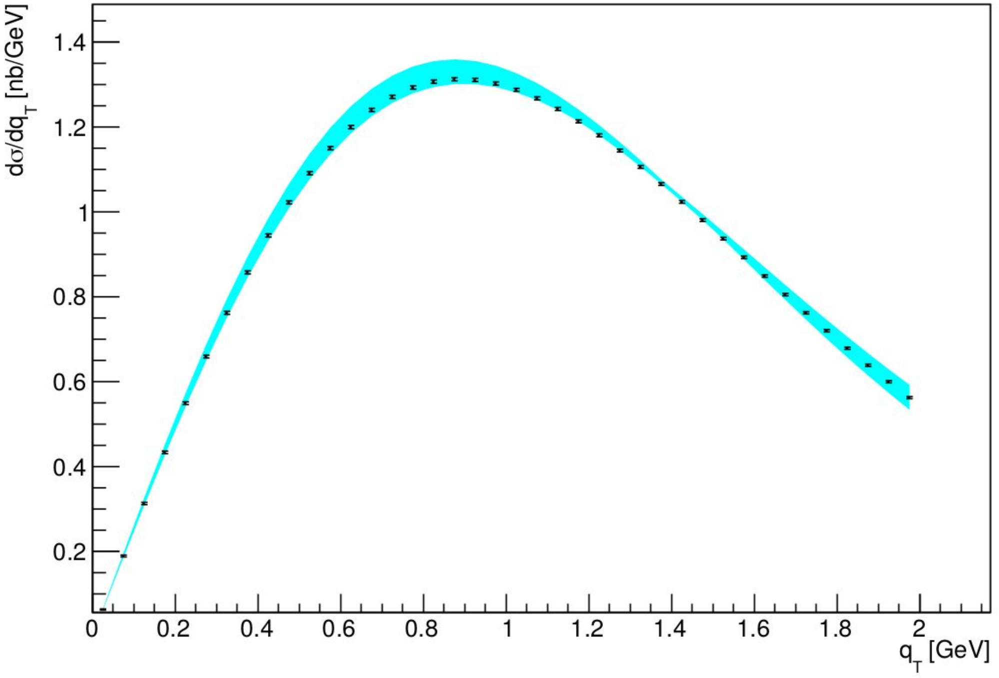
Measuring jet q_T spectrum at BELLE II

We know we have enough large enough datasets at Belle II

Predicted **statistical** uncertainties with 10 fb^-1

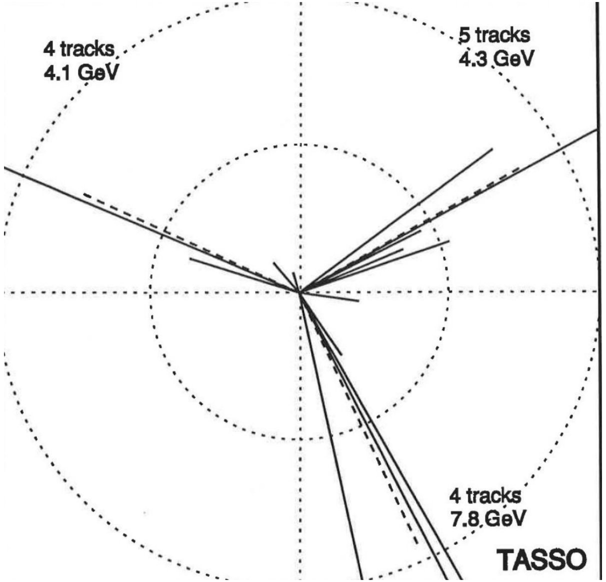
based on MC:

This shows how the statistical uncertainties (bars) would compare with the uncertainties of the prediction (band) if the shape were to agree

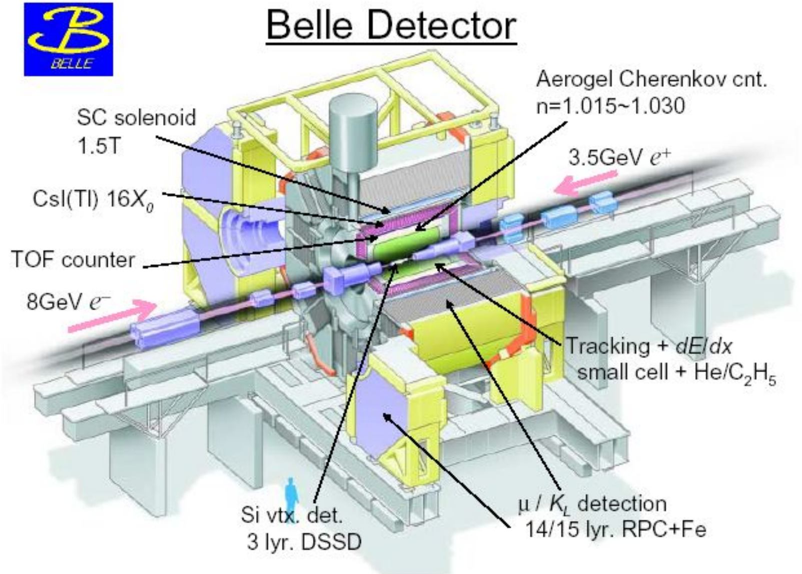


QCD and jet physics in e^+e^- collisions

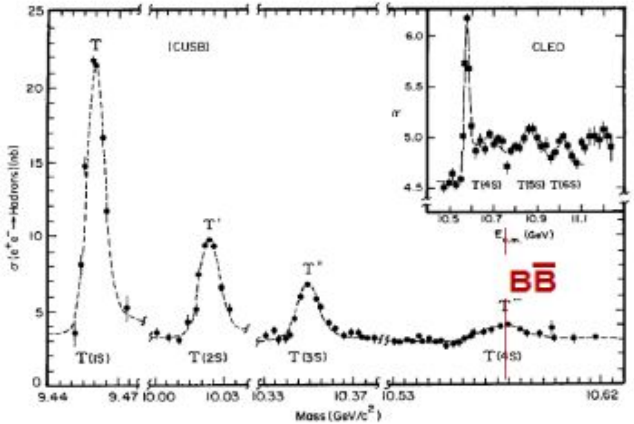
- Has long history in studying QCD
  - e.g. PETRA at DESY: discovery of the gluon (1979)



Belle Experiment (1999 - 2010)

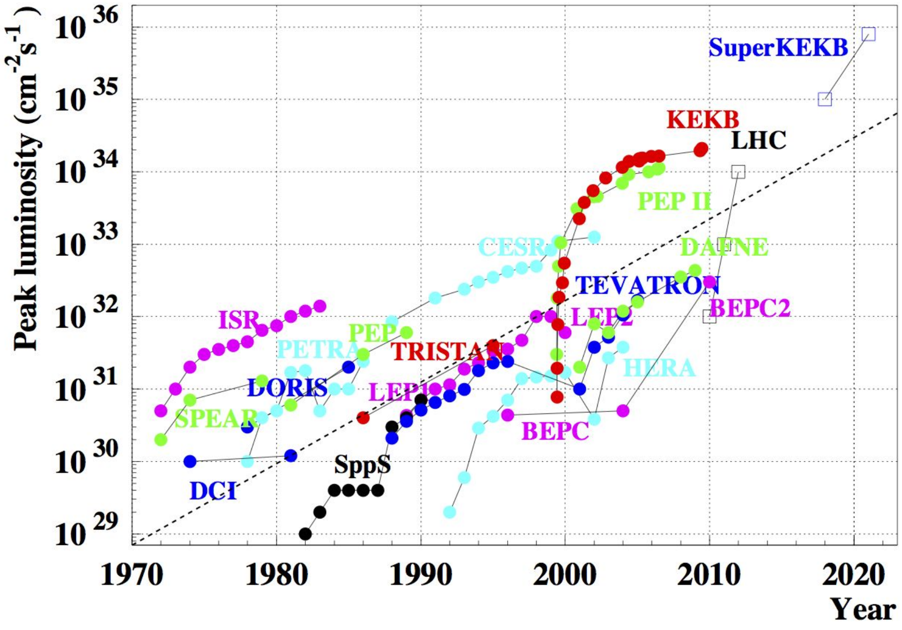


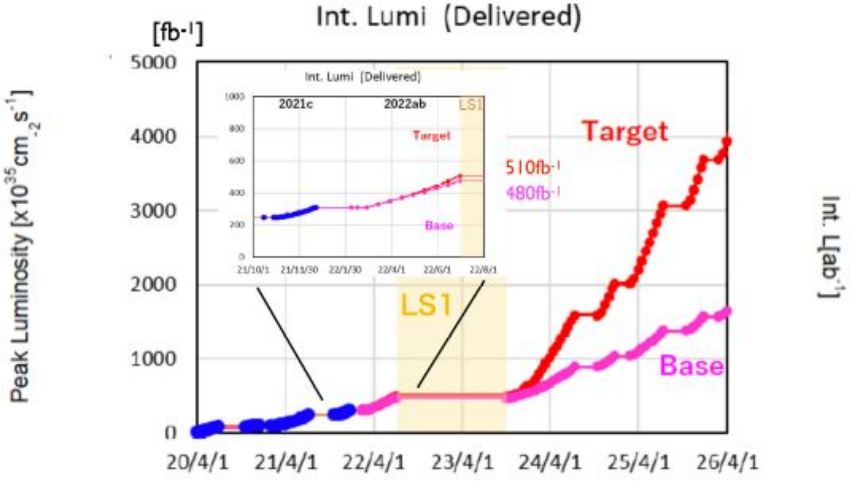
Exp.	Scans / Off-res. fb^{-1}	$\Upsilon(5S)$ 10876 MeV fb^{-1}	10^6	$\Upsilon(4S)$ 10580 MeV fb^{-1}	10^6	$\Upsilon(3S)$ 10355 MeV fb^{-1}	10^6	$\Upsilon(2S)$ 10023 MeV fb^{-1}	10^6	$\Upsilon(1S)$ 9460 MeV fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25	158	6	102



From: *PTEP* 2019 (2019) 12, 123C01, *PTEP* 2020 (2020) 2, 029201

The next-generation B-factory: SuperKEKB



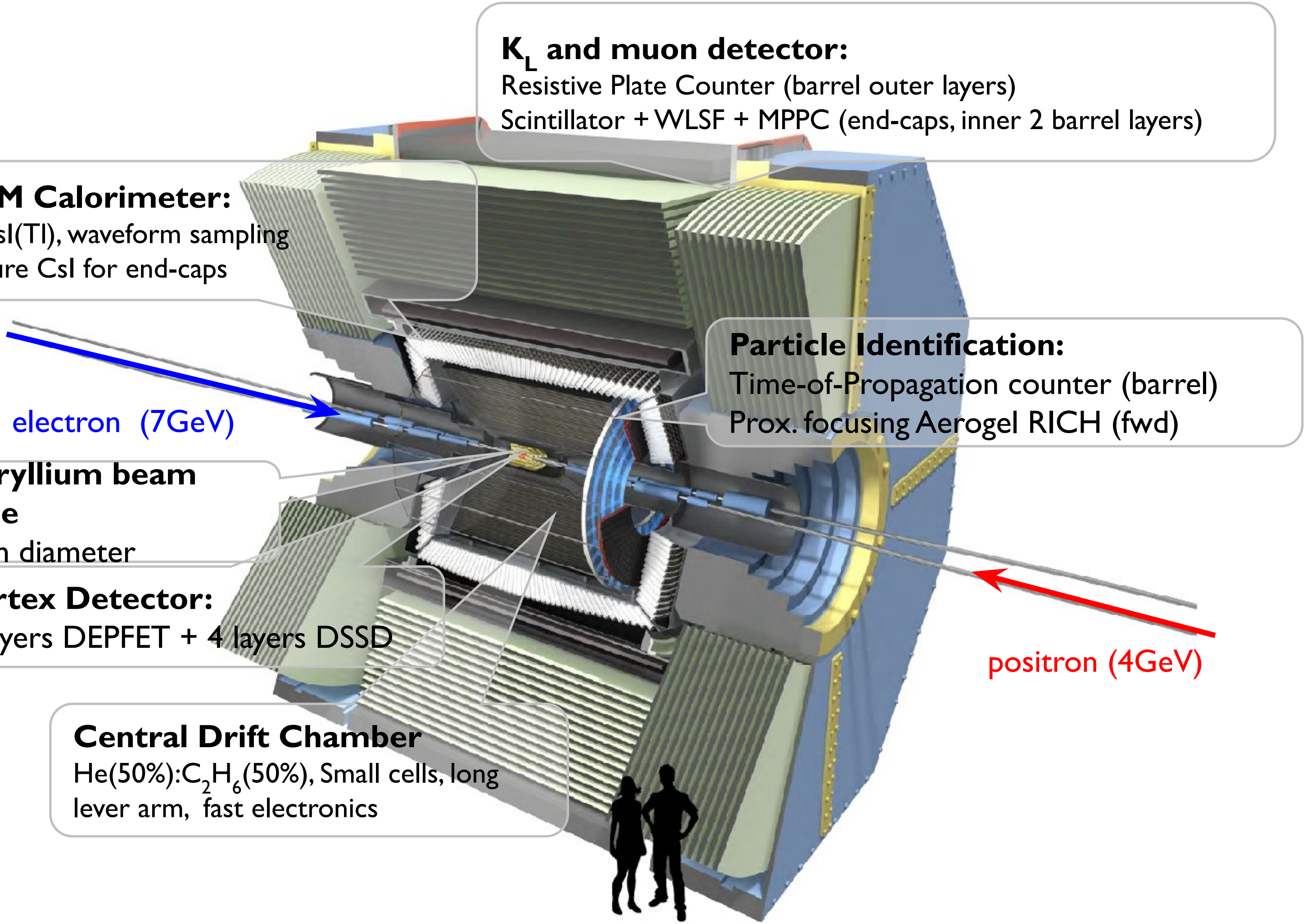


Beam currents *only* a factor of two higher than KEKB (~PEPII)

"nano-beams" are the key; vertical beam size is 50nm at the IP

- World record luminosity
- Expecting 50 x Belle integrated luminosity (100 x BaBar)

Belle II



K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
EM Calorimeter:
CsI(Tl), waveform sampling
Pure CsI for end-caps
Particle Identification:
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)
electron (7GeV)
Beryllium beam pipe
2cm diameter
Vertex Detector:
2 layers DEPFET + 4 layers DSSD
positron (4GeV)
Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

Physics Motivation and Goals

- We are interested in the structure of the proton
- We hope to extract PDFs from SIDIS at the EIC with increased precision
- Complication in SIDIS: both initial- and final-state non-perturbative physics
- In SIDIS, replacing nonperturbative TMD FFs with calculable jet functions increases sensitivity to initial state nonperturbative physics
- Jet functions receive nonpert. corrections for small transverse momenta
- Because of jet functions' universality (nonpert. structure), can use e^+e^- data

"[...] data from e^+e^- collisions could be used to fit a model for nonperturbative corrections to the jet function to be later applied to SIDIS"

Main results of paper by Gutierrez-Reyes et al.

- Proposal: measure jets instead of hadrons
  - Replacing TMD FFs with (new) TMD jet functions
  - When using WTA (winner-take-all), can use same factorization formulae
- Calculated Jet functions at one-loop level
- Phenomenological results for e^+e^- and SIDIS (q_T-spectra)
  - two-loop jet functions for large R limit -> N^3LL accuracy
  - large R limit describes full R results well

What datasets to use?

- Can use both on- and off-resonance
  - Gutierrez-Reyes et al. calculated for sqrt(s) = 10.52 GeV
    - Variation between dataset types expected smaller than ISR corrections
  - Ideally, proper dijet selection criteria are able to use the appropriate events from any set
  - If sufficient quantity, off-resonance could be easier to correct
- Use respective equivalent MC for unfolding (ideally 5-10 times as much data)

Track cuts / particle selection

- Using standard quality cuts and PID
  - Currently using the most-likely particle lists provided in basf2
  - photons, pi+, K+, protons, electrons, muons and respective anti-particles
- Photon cut in E to remove noise
  - Currently require photons to be E > 0.1 GeV
  - If not removed this could falsely add energy to the jets
  - This can be refined to detector-area specific cut-offs

Jet definitions

- Gutierrez-Reyes et al. calculate q_T spectra for anti-k_t with WTA
- Starting with this choice, perhaps comparing later

Jet definitions (for e+-e-)

c.f. fastjet documentation section 4

4.5 Generalised k_t algorithm for e^+e^- collisions

FastJet also provides native implementations of clustering algorithms in spherical coordinates (specifically for e^+e^- collisions) along the lines of the original k_t algorithms [25], but extended following the generalised pp algorithm of [14] and section 4.4. We define the two following distances:

$$d_{ij} = \min(E_i^{2p}, E_j^{2p})\frac{(1-\cos\theta_{ij})}{(1-\cos R)}\,, \tag{9a}$$

$$d_{iB} = E_i^{2p}\,, \tag{9b}$$

for a general value of p and R. At a given stage of the clustering sequence, if a d_{ij} is smallest then i and j are recombined, while if a d_{iB} is smallest then i is called an "inclusive jet".

For values of $R \leq \pi$ in eq. (9), the generalised e^+e^- k_t algorithm behaves in analogy with the pp algorithms: when an object is at an angle $\theta_{iX} > R$ from all other objects X then it forms an inclusive jet. With the choice $p = -1$ this provides a simple, infrared and collinear safe way of obtaining a cone-like algorithm for e^+e^- collisions, since hard well-separated jets have a circular profile on the 3D sphere, with opening half-angle R. To use this form of the algorithm, define

```
JetDefinition jet_def(ee_genkt_algorithm, R, p);
```

4.6 k_t algorithm for e^+e^- collisions

The e^+e^- k_t algorithm [25], often referred to also as the Durham algorithm, has a single distance:

$$d_{ij} = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})\,. \tag{10}$$

Note the difference in normalisation between the d_{ij} in eqs. (9) and (10), and the fact that in neither case have we normalised to the total energy Q in the event, contrary to the convention adopted originally in [25] (where the distance measure was called y_{ij}). To use the e^+e^- k_t algorithm, define

```
JetDefinition jet_def(ee_kt_algorithm);
```

Unfolding

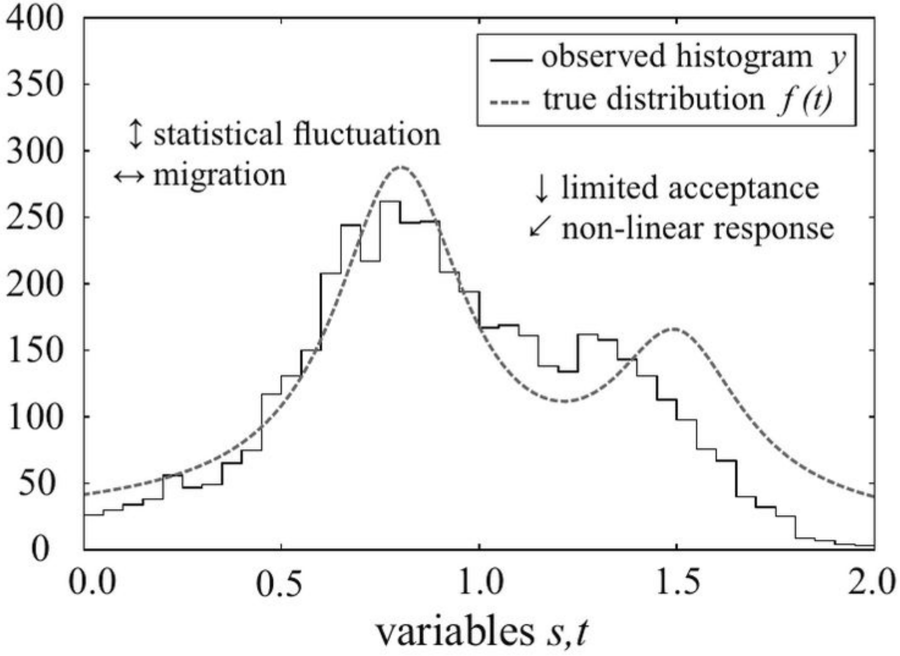


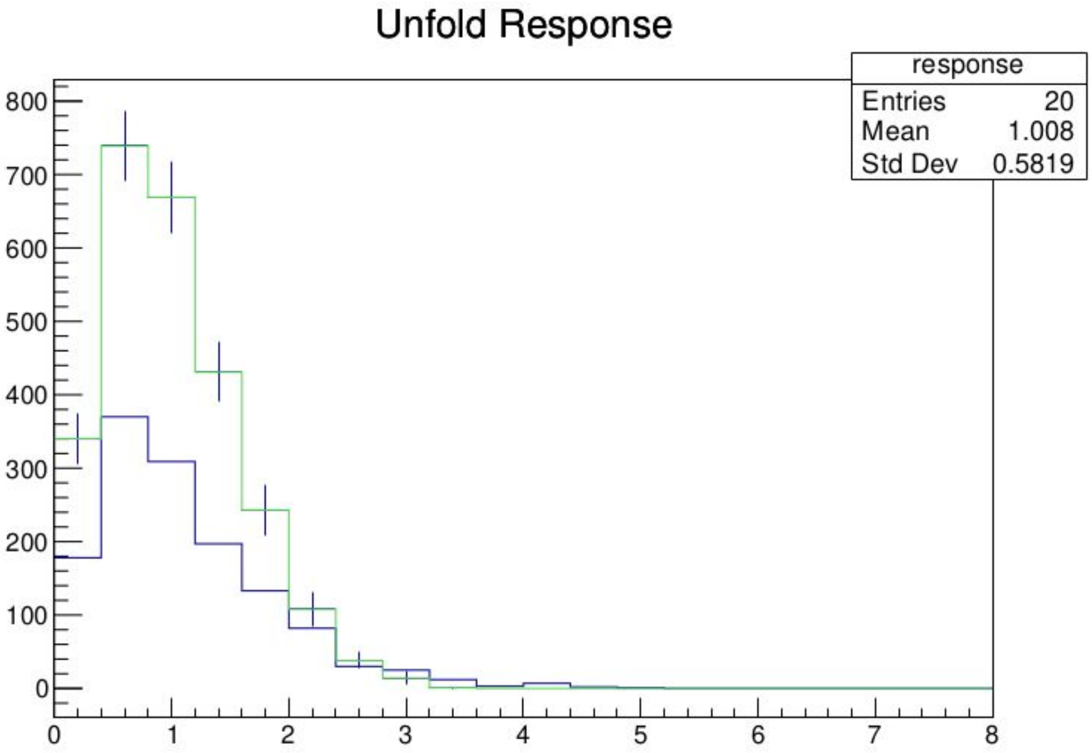
Figure 6.1 Illustration of the unfolding problem. The true distribution $f(t)$ of a variable t to be measured in a particle physics experiment is shown. A corresponding simulated measurement $g(s)$ is shown as histogram y. See the text for further details.

Multiple effects to consider:

- statistical fluctuations
- horizontal migration
- limited detector acceptance
- “non-linear response”
- additional backgrounds

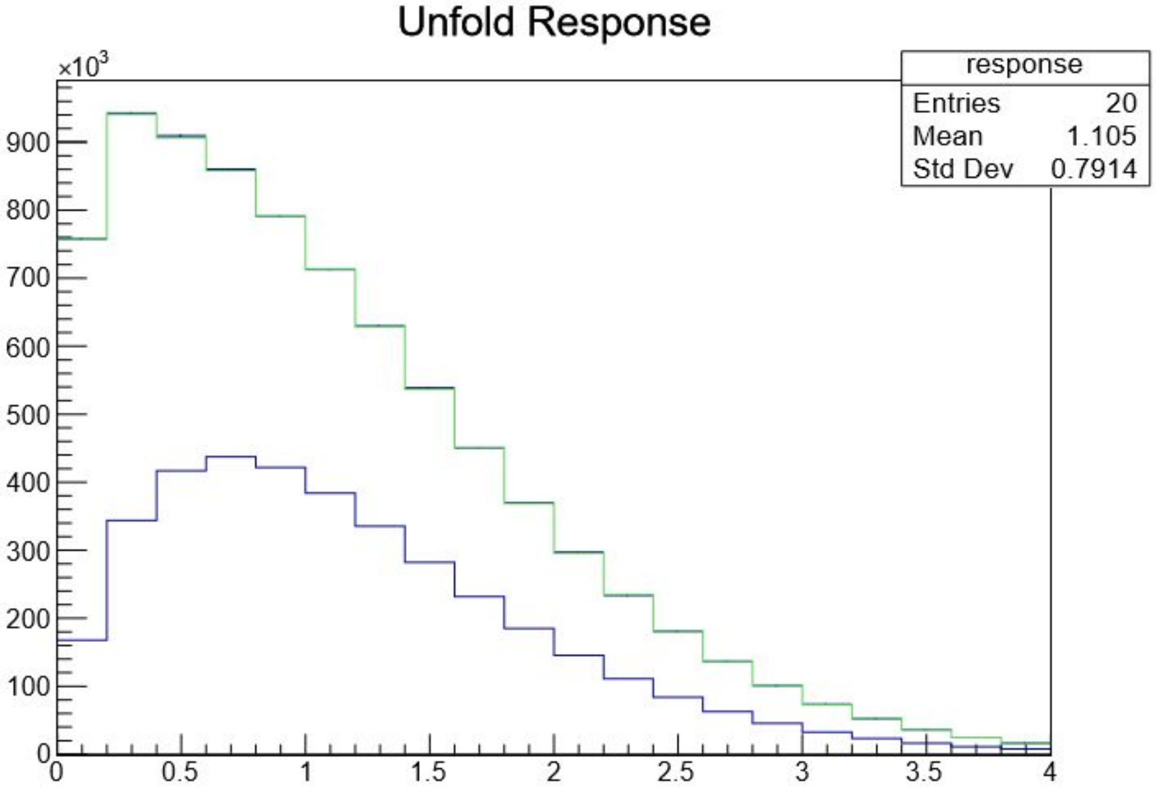
Unfolding

- First a simple check:
  - Use same sample for response and unfolding
  - Bayes Unfolding (4 iterations)
  - AntiKt test file



On larger (uubar) MC sample

Closure tests check out

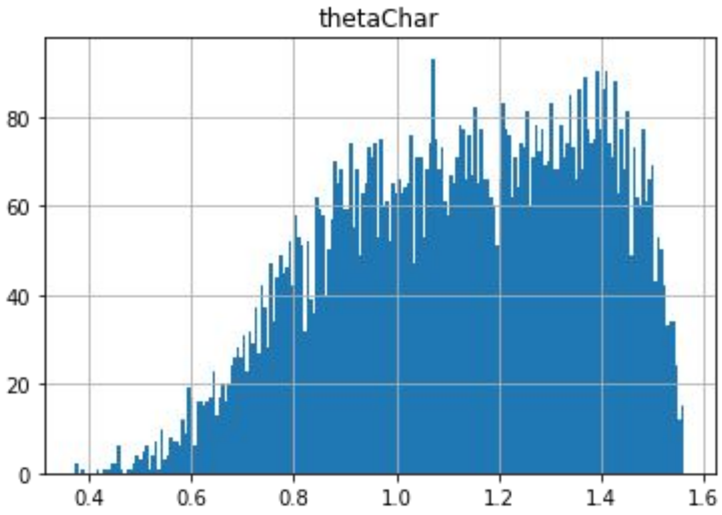


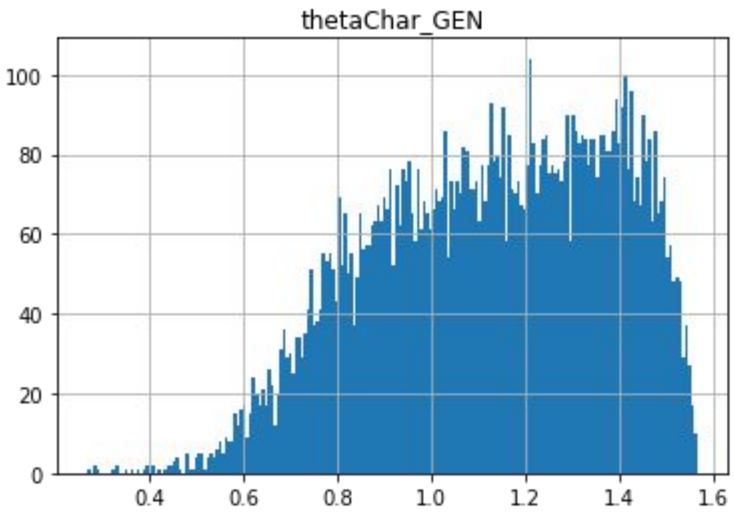
Unfolding in polar angle

- Detector response is expected to depend on the orientation of the dijet
- Need to find a quantity to represent this orientation
    - e.g. thrust angle, one of the jet axes, etc.
- Implemented (unweighted) average angular distance from beam line of the two dominant jets

Unfolding in polar angle

- This quantity is very similar between truth and reconstructed dijet events that pass dijet event cut

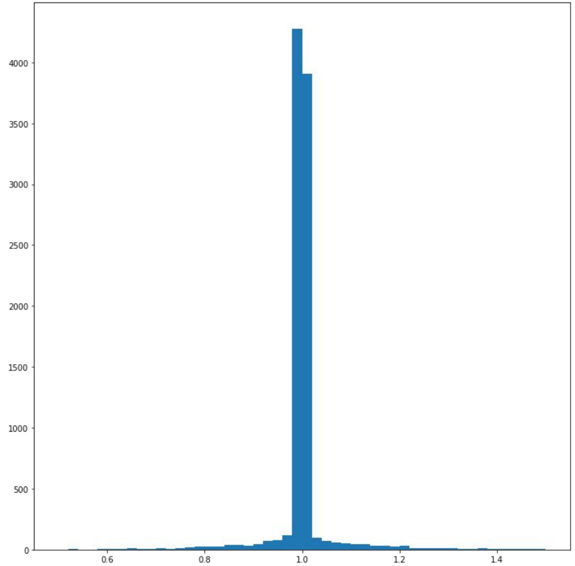


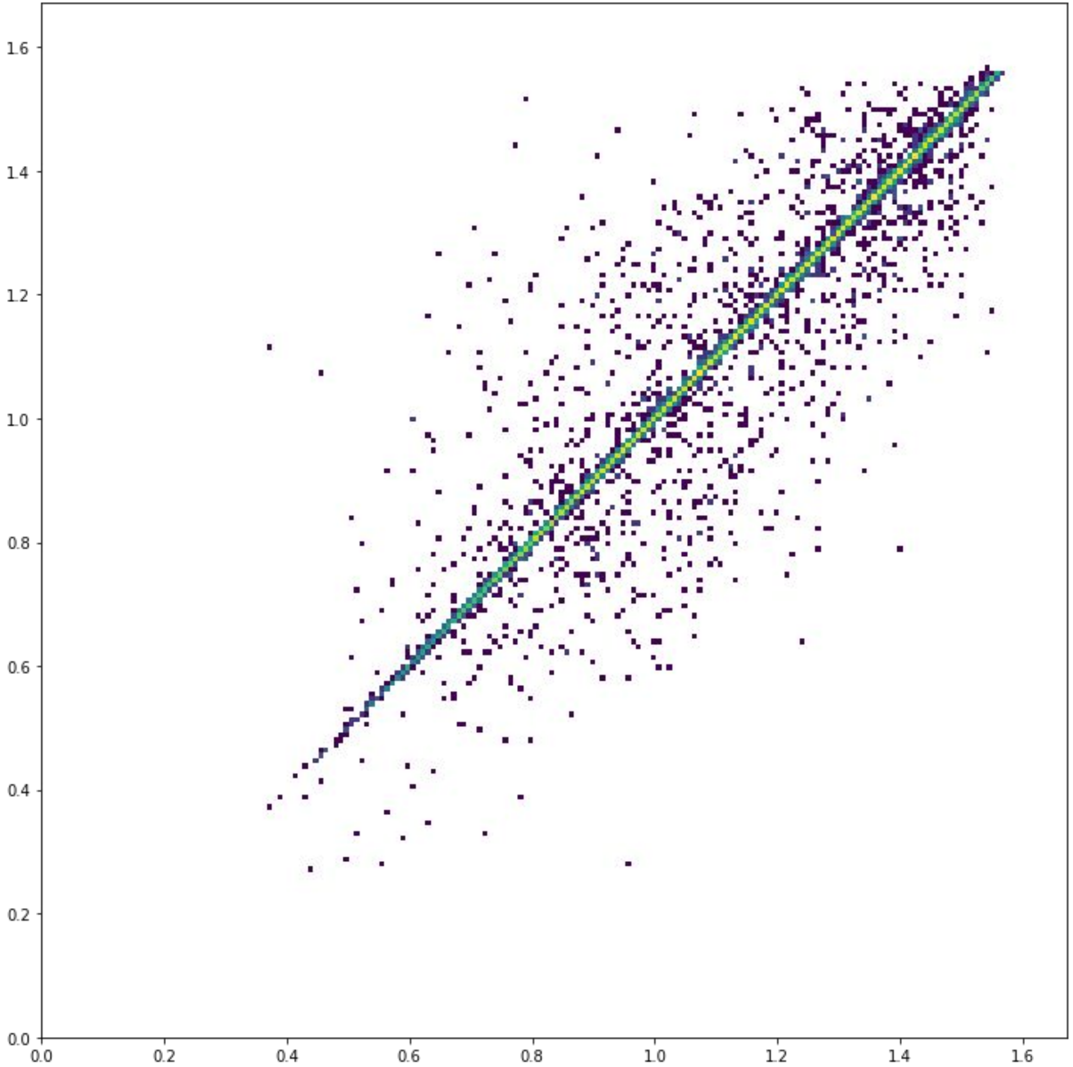


x-axis: reconstructed

y-axis: generated

below: ratio recon/truth





Non qqbar corrections

Different event types have different cut-efficiencies

Checked how many events pass the 3.75 GeV cut-off for dijet selection

- BBbar events highly suppressed

	uubar	ddbar	ssbar	ccbar	charged	mixed	taupair
MC truth	0.497	0.457	0.328	0.264	0.00864	0.00584	0.0809
MC reconstructed	0.101	0.0888	0.0629	0.0538	0.0035	0.00231	0.0327

Current status

- Can calculate q_T from given event (in data and MC)
- Code is set up to compare MC truth with reconstructed
- Built event visualization to check and compare jet-clustering and event-selection
- Working on the unfolding procedure

The Time-reversal Odd Side of a Jet

Xiaohui Liu[1,2,*] and Hongxi Xing[3,4,†]

[1] *Center of Advanced Quantum Studies, Department of Physics, Beijing Normal University, Beijing 100875, China*

[2] *Center for High Energy Physics, Peking University, Beijing 100871, China*

[3] *Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*

[4] *Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou 510006, China*

We re-examine the jet probes of the nucleon spin and flavor structures. We find for the first time that the time-reversal odd (T-odd) component of a jet, conventionally thought to vanish, can survive due to the non-perturbative fragmentation and hadronization effects. This additional contribution of a jet will lead to novel jet phenomena relevant for unlocking the access to several spin structures of the nucleon, which were thought to be impossible by using jets. As examples, we show how the T-odd constituent can couple to the proton transversity at the Electron Ion Collider (EIC) and can give rise to the anisotropy in the jet production in e^+e^- annihilations. We expect the T-odd contribution of the jet to have broad applications in high energy nuclear physics.

The azimuthal asymmetry takes the general form [48]

$$R^{J_1 J_2} = 1 + \cos(2\phi_1) \frac{\sin^2\theta}{1+\cos^2\theta} \frac{F_T(q_T)}{F_U(q_T)}, \tag{9}$$

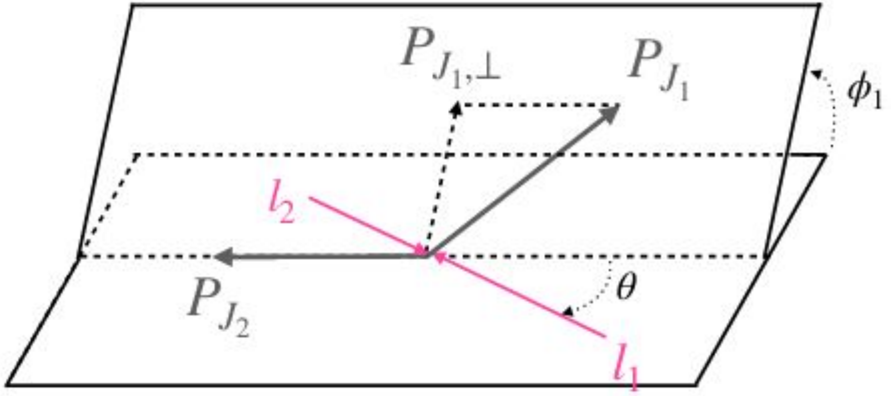


FIG. 4. Kinematics in the e^+e^- annihilation.

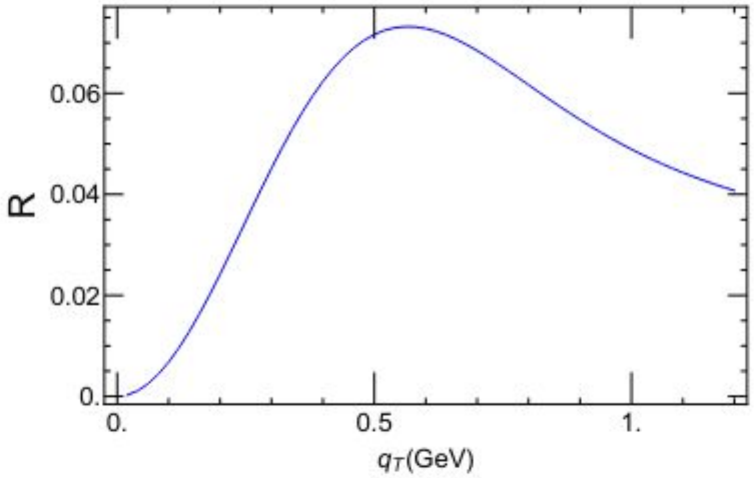


FIG. 5. Azimuthal asymmetry induced by the T-odd jets as a function of q_T in e^+e^-.

In Fig. 5, we present a prediction for the azimuthal asymmetry $R = 2\int d\cos\theta \frac{d\phi_1}{\pi}\cos(2\phi_1)R^{J_1J_2}$ with $\sqrt{s} = \sqrt{110}\,\text{GeV}$. We can see a non-vanishing azimuthal asymmetry induced by the T-odd jet. The actual magnitude and shape of this asymmetry should be determined by upcoming experimental data analyses. Similar azimuthal anisotropy can also be shown to exist in the dijet production in both pp and heavy ion collisions, whose studies will be investigated in the future.

T-odd jets: measurement in practice

- Dijet event selection with similar criteria as for q_T spectrum
- Extracting φ_1, θ, and q_T for each event
- For selected q_T bin, fit distribution of φ_1 values
  - Simply average over θ, or use θ bins?
- Fit is then comparable with calculations for $R^{J_1 J_2} = 1 + \cos(2\phi_1)\frac{\sin^2\theta}{1+\cos^2\theta}\frac{F_T(q_T)}{F_U(q_T)}$,
- What systematic problems are to be expected?
  - Angle φ_1 problematic at low q_T?

arXiv:2205.01117

A Fragmentation Approach to Jet Flavor

Simone Caletti,[1] **Andrew J. Larkoski,**[2] **Simone Marzani,**[1] **and Daniel Reichelt**[3]

[1] *Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, 16146, Italy*

[2] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA*

[3] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE United Kingdom*

E-mail: simone.caletti@ge.infn.it, larkoski@slac.stanford.edu, simone.marzani@ge.infn.it, daniel.reichelt@durham.ac.uk

Abstract: An intuitive definition of the partonic flavor of a jet in quantum chromodynamics is often only well-defined in the deep ultraviolet, where the strong force becomes a free theory and a jet consists of a single parton. However, measurements are performed in the infrared, where a jet consists of numerous particles and requires an algorithmic procedure to define their phase space boundaries. To connect these two regimes, we introduce a novel and simple partonic jet flavor definition in the infrared. We define the jet flavor to be the net flavor of the partons that lie exactly along the direction of the Winner-Take-All recombination scheme axis of the jet, which is safe to all orders under emissions of soft particles, but is not collinear safe. Collinear divergences can be absorbed into a perturbative fragmentation function that describes the evolution of the jet flavor from the ultraviolet to the infrared. The evolution equations are linear and a small modification to traditional DGLAP and we solve them to leading-logarithmic accuracy. The evolution equations exhibit fixed points in the deep infrared, we demonstrate quantitative agreement with parton shower simulations, and we present various infrared and collinear safe observables that are sensitive to this flavor definition.

Selection of $e^+e^-\to$dijet events: ISR effects

- Currently selected by requiring that two highest energy jets have E > 3.75 GeV each (z > 0.713)
- Noticed contamination from events that look like ISR or only photons in MC

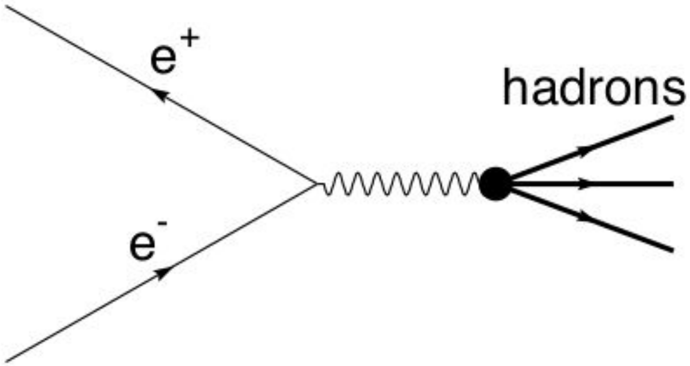


Figure 21.2.1. The lowest-order Feynman diagram describing the process of e^+e^- annihilation into hadrons.

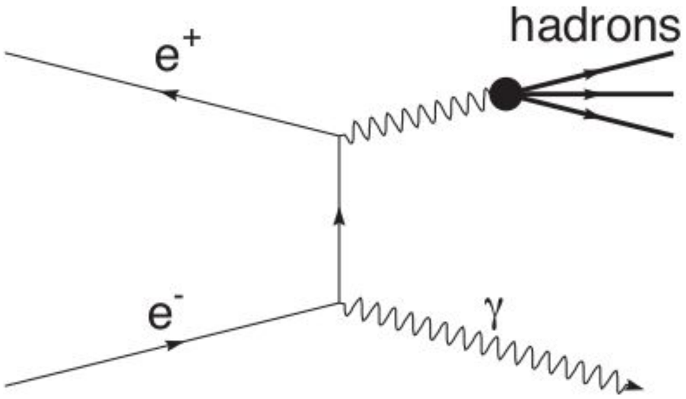


Figure 21.2.2. The lowest-order Feynman diagram describing the process of $e^+e^- \to \gamma_{ISR} + \text{hadrons}$.

source: Bevan, Adrian, et al. *The physics of the B factories.* Springer Nature, 2017.

Jets: Software

There is a convenient software package for both pp and e^+e^- experiments:

FastJet (http://fastjet.fr/)

"*A software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation.*"

Even more convenient: FastJet has been included in the basf2 externals v01-10-00 and newer

Additions to SConscript file to allow access:

```
Import('env')

env['CPPPATH'] += ['/cvmfs/belle.cern.ch/el7/externals/v01-11-00/include/']

env['LIBPATH'] += ['/cvmfs/belle.cern.ch/el7/externals/v01-11-00/Linux_x86_64/common/lib']

Return('env')
```